REVIEW ARTICLE

Scanning impedance microscopy (SIM): A novel approach for AC transport imaging

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Abstract

Scanning Impedance Microscopy (SIM) is one of the novel scanning probe microscopy (SPM) techniques, which has been developed to taking image from sample surface, providing quantitative information with high lateral resolution on the interface capacitance, and investigating the local capacitance–voltage (C–V) behavior of the interface and AC transport properties. The SIM is an ordinary AFM equipped with a conductive tip (C-AFM), which is imaged by non-contact mode with harmonic detection. This method is based on the local detection of surface potential or the amplitude and phase of local voltage oscillations induced by a lateral periodic bias applied across the sample. SIM can simultaneously collect the amplitude and phase signals and image the morphology of the surfaces; afterward, calculate the corresponding histogram for each map. Hence, the amplitude and phase signals of the surface potential oscillations are related to the sample impedance. SIM can also be integrated with Surface Potential Microscopy (SSPM). The combination of these techniques provides an approach for the quantitative analysis of local DC and AC transport properties. These advantages give SIM a higher resolution than other SPM techniques and indicate its immense potential for vast applications. The combination of SSPM and SIM were demonstrated for a Schottky diode, but can be applied to any semiconductor device.

Keywords: *Impedance; Local transport properties; Scanning impedance microscopy; Scanning probe microscopy; Surface potential oscillations.*

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INTRODUCTION

The study of electronic devices properties, their performance and interface related phenomena have always been considered as an interesting research area. Some researchers have investigated fundamental probe-surface interactions and developed scanning probe based characterization techniques (SPM) to study local electronic, magnetic and dielectric properties [1-6]. The SPM family has opened a new unique opportunity to measure surface topography and probe the various mechanisms on nano-scale, which will be crucial different applications [1-3, 7-8]. Among the several SPM's techniques, scanning force microscopy (SFM) is one of the most widely utilized methods which its main techniques have long been used for nano-scale electrical measurements as illustrated in Table 1 [9].

In general, the SFM's methods can be categorized into current and force sensing techniques. In current sensing methods, a conductive probe with a sharp tip is used for measuring of the current flowing throughout the sample with high resolution, while simultaneously probing the surface topography under force feedback control. These techniques have been divided to some sub techniques (Table 1) and utilized to characterize the electrical transport properties of several samples such as carbon nanotubes (CNTs), self-assembled monolayers, thin dielectric films, single proteins, nano-scale electronic tools and circuits. The techniques on the base of force sensing, is applied to investigate the surface electrical properties such as surface potential, surface charge and dielectric constant by measuring the electrostatic interaction force between the probe and the sample [10-11]. Among the several force sensing techniques, this overview aims to present of the innovative Scanning Impedance Microscopy (SIM) method, which is a member of SPM/

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SFM family (Table 1) [10]. SIM is a force sensing technique based on detection of phase shift of the cantilever oscillation induced by lateral AC bias applied to the surface, which it can measure the phase and amplitude of local voltage oscillations induced by a lateral periodic bias applied across the macroscopic electrodes [11-12]. This technique acts as similarly to conventional four-probe resistance measurements, in which AFM tip is used as a moving electrode, giving the advantage of spatial resolution. It is also worth mentioning that characterization of AC transport properties has long been measured by impedance spectroscopy (IS) technique, which Impedance spectroscopy is the most a versatile tool for semiconductor characterization. One of the primary limitation of IS technique is lack of spatial resolution of this method to predict the equivalent circuit components from being unambiguously associated with individual microstructural features. SIM provide quantitative determination of frequency and bias dependent interface properties of electrically inhomogeneous materials with high lateral resolution and precision that can solve this problem [12-13]. In this overview, scanning impedance spectroscopy method and its capabilities, applications and role of this technique for imaging transport behavior in nano-electronic devices is presented. Moreover, the SIM imaging mechanism is describe in detail. Ultimately, the combination of SIM and Surface Potential Microscopy (SSPM), sometimes referred to as Kelvin Probe Microscopy (KPM) is investigated as a quantitative tool for providing of local AC and DC transport properties of the interface and spatially in semiconductor devices or complex microstructures.

Basic Concepts of Scanning Impedance Microscopy

Scanning Impedance Microscopy (SIM), as a member of SPM/SFM family, is based on the interaction of a probe tip and a surface similar to other these microscopes, that operates based on the principle of force sensing with different detection system [10-11]. In the SIM, a modulating electric signal is applied laterally through the surface and this feature makes it different from other probe microscopies [13]. The SIM is an ordinary conductive atomic force microscopy (C-AFM) which has been connected to a resonator and to the lock-in amplifier (Fig. 1a) [13]. As observed in Fig. 1b, the tip-sample separation is maintained constant (the lift height for the interleave scans is usually 50~100 nm), and the instrument gathers data in lift mode and the dynamic electrostatic interactions response can be detected. In lift mode, the surface topography is first obtained in contact mode after which the tip is separated a preset distance from the surface and scanned the sample surface (non-contact mode).

The cantilever responds to an oscillating electrical signal and lock-in system determines the phase and amplitude of tip vibration. Sugawara et al. found that, usual contact mode imaging due to damage of the sample or displacement is rather destructive and the large contact force severely impairs the spatial resolution [14-15].

SIM method is imaged by non-contact mode with harmonic detection by responding of cantilever to an oscillating electrical signal. In this technique imaging measurements are performed in constant voltage changes (ΔV) mode [16-20]. The applied oscillating signal can be varied in the range of a few kHz. On the other hand, it can be operated in contact or near-contact mode, which is similar to macroscopic impedance spectroscopy and is referred to as nano impedance microscopy (NIM) or nano impedance spectroscopy (NIS) [5]. The SIM and NIM (NIS) techniques are compared in Table 2 [17-18].

Table 1: Main scanning force microscopy (SFM) techniques. Highlighted is the Scanning Impedance Microscopy (SIM) technique reviewed in this paper [10].

Scanning Force Microscopy (SFM)				
Current Sensing				
Base of technique	Resonant frequency detection	Current Fluctuations	AC Current	Dc Current
Technique	Scanning Capacitance Microscopy (SCM)	Electrical Noise Microscopy (ENM)	Nano-scale Impedance Microscopy (NIM)	Conductive Atomic force Microscopy (C-AFM)
Force Sensing				
Technique	Electrostatic Force Microscopy (EFM)	Scanning Impedance Microscopy (SIM)	Kelvin Probe Force Microscopy (KPFM)	

Table 2: Properties and modulated operation modes of SIM and NIM (NIS) canning Probes [17-18].

Technique	Scanning Impedance Microscopy (SIM)	Nano Impedance Microscopy (NIM)
Operation Mode	Non-contact	Contact
Detection	Cantilever responds to an oscillating electrical signal	Constant force feedback
Signal	Phase and amplitude	Frequency spectrum
Properties	Interface potential, capacitance time constant, local band energy, potential, current flow (in comb. w/ SSPM)	Interface potential, capacitance, time constant, dopant profiling

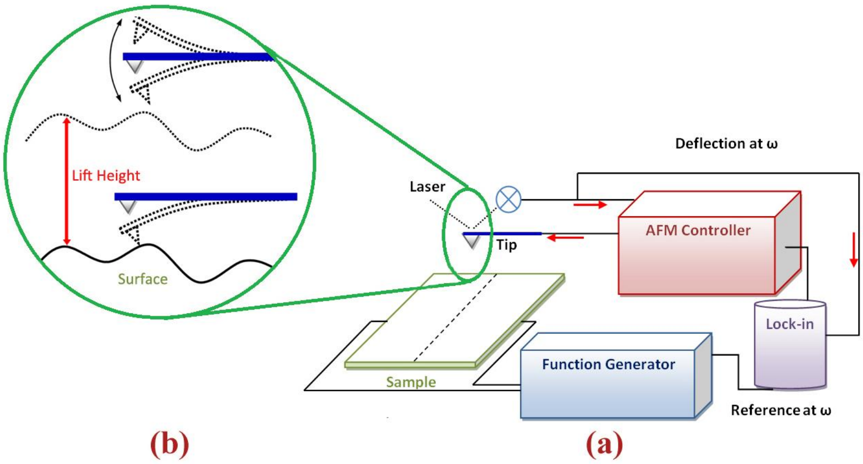

Fig. 1: Schematics of the SIM experimental set-up (a) [13]; the instrument operating in lift mode (b) [17].

SIM is equipped with a lock-in amplifier and function generator. In SIM the quantities of ratio of oscillation amplitudes and phase shift across the interface are dependent solely by frequency dependent impedance of the interface and the circuit and independent of the tip and cantilever properties [17].

The SIM imaging provides quantitative information on the transport properties (interface capacitance and local capacitance–voltage (C–V) behavior) of the interface. The validity of SIM was also verified against a metal-semiconductor interface (Schottky diode) on which this approach was used to obtain local C-V and I-V characteristics of the interface with lateral resolution of about 50 nm or better [13, 21]. It is noted that, in order to determine the effect of defects on the local electronic structure of an individual defect, the frequency dependence can be added to SIM to a configuration that isolates a single wire. This approach has been reported for carbon nanotube circuit for imaging transport behavior in nanoelectronic devices and can be also generalized to all classes of molecular wires. The SIM measurements can be performed in systems with high dielectric constants, semiconductors, nanoelectronic and molecular electronic devices, etc [13, 17].

AC Transport Properties by SIM

Additional information about the sample can be obtained by investigation of the frequency variation which provides a path to obtain local electronic transport properties. The "impedance" is the ratio between the applied voltage variation and current response, Z(ω)= V(ω)/I(ω)= I Z I exp (iΘ) [18]. Providing the frequency resolved impedance amplitude (Z), and phase (ϕ), gives information about the capacitance, resistance and relaxation times associated with transport processes [5, 18]. Hence, the SIM signal amplitude (A_{SIM}) and phase (ϕ_{SIM}) of the surface potential oscillations corresponding to the equivalent circuit model is related to the sample impedance data and can be measured at the nanometer scale by Equations (1) and (2), respectively.

$$A_{\mathrm{SIM}} = \frac{RV_{hf}}{\sqrt{[R+\mathrm{Re}(Z^*)]^2 + \left[\left(\omega L - \frac{1}{\omega C}\right) + \mathrm{Im}(Z^*)\right]^2}}, \quad (1)$$

$$\varphi_{\mathrm{SIM}} = \arctan\frac{\left(\omega L - \frac{1}{\omega C}\right) + \mathrm{Im}(Z^*)}{R + \mathrm{Re}(Z^*)}, \quad (2)$$

In fact, A_{SIM} and ϕ_{SIM}, are the response of the cantilever to the periodic force. Where R, C, L, ω, and V_{hf} are the characteristics of the resonator circuit, while Z* is the complex impedance and is modeled by an ideal equivalent circuit consisting of capacitors and resistors [19]. It should be noted that, an electroactive interface can be modeled as a simple RC element (a parallel resistor-capacitor), which the corresponding equivalent circuit is shown Fig. 2. In this technique, tip is held at constant bias (V_{dc}) and a lateral bias (V_{lat}) in Eq. (3). V_{surf} induces an oscillation in surface potential according to Eq. (4).

$$V_{lat}= V_{dc} + V_{ac} \cos (\omega t) \quad (3)$$

$$V_{surf}= V_s + V_{ac} (x) \cos [\omega t + \phi (x)] \quad (4)$$

In fact, the lateral bias simultaneously induces an oscillationin surface potential, where V_s , ϕ (x) and V_{ac} (x) are DC surface potential, the position dependent phase shift and voltage oscillation amplitude, respectively [13,17, 21]. However, with obtaining of the relationship between voltage oscillation amplitude and cantilever oscillation amplitude, V_{ac} (x) is mapped directly. Under some simple assumption, the phase lag between the cantilever oscillation and surface voltage can be constant; hence, by calculating of the mechanical oscillations phase of the cantilever position dependent phase angle of voltage oscillations, ϕ (x), is achieved [13,17]. Noteworthy, frequency dependent phase shift and amplitude are obtained by SIM. Because of relationship between of electrostatic force gradients and the non-uniform surface potential, the driving frequency must be selected far from the resonant frequency of the cantilever in order to minimize the variations of the phase lag between tip and surface [21]. Imaging is possible at the low frequencies; in addition, spectroscopic measurement can be performed in all frequency ranges below cantilever resonant frequency [22]. The tip oscillation amplitude is proportional to the local voltage oscillation amplitude and constitutes the SIM amplitude image. Using SIM the amplitude and phase signals and topography can simultaneously be obtained and the corresponding histograms for each map calculate.

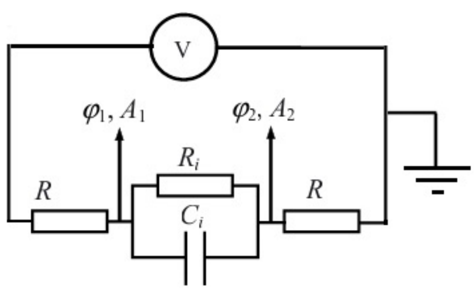

Fig. 2: The corresponding equivalent circuit for AC transport measurements by Scanning Impedance Microscopy (SIM) [13, 19].

Also, the profiles of phase across the interface (for lateral DC biases), frequency dependence of phase shift of the interface and frequency dependence of SIM phase on the left and right of the interface for different circuit terminations can be obtained. Furthermore, additional information about the fine structure from the amplitude and phase profiles can be achieved [13, 19-21].

The combination of SSPM and SIM

The combination of Scanning Surface Potential Microscopy (SSPM) and SIM has been investigated for the possibility to determine the local transport properties. Similar to SIM technique, SSPM is based on the force sensing and measuring the electrostatic interaction between the probe and the sample in non-contact mode [17]. In SIM, local potential variations induced by the lateral AC voltage applied throughout the sample can be detected and directly addressed to AC transport properties. But, in SSPM the tip as a moving voltage probe scan sample surface and the variations of local potential associated with the ohmic losses within the grains is detected and the study of DC transport properties is possible [23]. Both of these techniques are independent to the tip and cantilever properties. These techniques can measure the local properties with a resolution of ~100 nm [23] and these are sensitive to local potential variations (SSPM) or the oscillation of local voltage phase and amplitude (SIM), rather than to current [13,18]. Also, some researchers have been focused on the relationship between SIM and SSPM images and information obtained from DC transport measurements and traditional impedance spectroscopy [13, 18, 21]. Combination of these techniques is used to provide local voltage and I–V characteristics of the interface and spatially resolved impedance spectra of complex microstructures [17, 21, 23]. Besides, when the SIM is complemented by SSPM, provides spatially localized impedance spectroscopy of the material directly [12]. In addition, the applicability of this combination for quantitative determination of interface C-V curve and imaging transport behavior in different frequency regimes for various materials are investigated [12-13, 17, 21, 23]. The obtained results of SIM/SSPM technique for the quantification of the interface transport properties is remarkably similar to conventional C-V and four-probe impedance spectroscopy measurements [17]. The applicability of SIM and SSPM for imaging and quantitative characterization of AC and DC transport properties of nanoelectronic devices is obtained [21, 24]. This combination is a good candidate for the characterization of local AC and DC transport properties in semiconductor devices on micron/submicron development [21].

The other advantage of SIM/SSPM technique is the spatial localization of microstructural elements with capacitive and resistive behavior, which can be then compared to AFM and electron microscopy (TEM, SEM, HRTEM, etc) techniques. If local behavior of the individual structural element and global frequency dependent impedance of the system have been simultaneously monitored, it can be expected that the combination of SIM and SSPM provide best results in conjunction. It is mentioned that if the measurements have been performed under ultra-high vacuum (UHV) conditions the spatial resolution and sensitivity of SIM/SSPM technique can be significantly improved [17].

DC Transport Properties by SSPM

In SSPM, a tip as a moving voltage probe is above the surface and a periodic field is applied; and the resulting force between the tip and sample can detect. SSPM measurements are performed from ~10 nm to 1.5 μm above the surface [17-18]. In the presence of a surface potential, the electrostatic force acting on the tip depends on the difference of tip-sample potential. In this method, the probing tip is biased directly by a DC voltage according to the Equation. (5) [17].

$$V_{tip} = V_{dc} + V_{ac}\cos(\omega t) \quad (5)$$

Where, V_{tip} is the tip DC bias, V_{dc} and V_{ac} is referred to as the nulling potential and driving voltage, respectively. Note that the overall circuit topology is required for reconstruction of DC transport properties from SSPM information [17]. Fig. 3 shows the corresponding equivalent circuit for AC transport measurements by SIM. Measurement in SSPM under lateral bias is based on potential drop at the interface as a function of external lateral bias (voltage characteristic of the interface). For inhomogeneous surfaces, because of the variation of work function along the surface, images of SSPM contain an additional contribution [21].

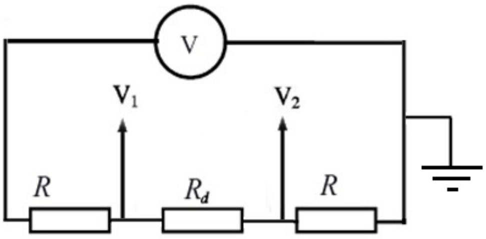

Fig. 3: The corresponding equivalent circuit for CD transport measurements by Scanning Surface Potential Microscopy. R and Rd are known current limiting resistors in the circuit and interface resistance, respectively. V1 and V2 are the surface potentials to the left and right hand side of the interface determined by SSPM [17].

When the instrument is adjusted to the open loop SSPM mode (the feedback is disengaged), tip oscillation in response to an AC bias is determined. Hence, the absolute value of local amplitude, $V_{ac}(x)$, is obtained. The oscillation of local voltage amplitude is then:

$$V_{ac}(x) = \frac{V_{ac} A_{sim}(x)(V_{surf}(x) - V_{tip}^{sspm})}{A_{sspm}(x)(V_{surf}(x) - V_{tip}^{sim})}, \quad (6)$$

Where V_{ac} and A are the tip AC bias and the oscillation amplitude, respectively. V_{tip} is the tip DC bias, and sim and sspm refer to SIM and open-loop SSPM modes, respectively. V_{surf} (x) is the surface potential which varies with x in the presence of a lateral bias and can be determined by SSPM [21]. The contribution of electrostatic force to the tip oscillation is nullified by adjusting a DC bias applied to the cantilever. Note that for a single electroactive interface, the analysis of the SSPM imaging mechanism is similar to that of SIM [17]. The SSPM image formation mechanism on the grounded surface was studied in details by Kalinin and Bonnell [25]. SSPM approach has been recently developed in order to image potential drops at laterally biased grain boundaries and to detect stray fields over Schottky double barriers in electroceramics and semiconductors [17, 22]. Although some efforts have been made to investigate the potential barriers at interfaces in laterally biased electroceramics and semiconductor devices, but few attempts have been done to characterize the transport properties of the interface directly from SSPM data [22]. The work of Shikler et al. showed that SSPM method can be used for nanometer detection of two-dimensional potential profiles at the semiconductor interfaces [26, 27].

CONCLUSION

Scanning Impedance Microscopy (SIM) is a type of a scanning probe technique based on the detection of the phase and amplitude change of cantilever oscillations induced by the lateral AC-voltage applied to the sample. Analysis of local AC transport properties is possible by this method. The traditional impedance spectroscopy (IS) has poor spatial resolution, while the SIM provides the advantages of this method and is known as a superior technique. This technique has been established as a quantitative tool for the characterization of local interface capacitance vs. potential drop at the interface (C-V) with lateral resolution. Furthermore, this technique can be integrated with scanning surface potential microscopy (SSPM).

The combination of SIM and SSPM on the laterally biased surface allows independent quantification of interface capacitance and resistivity. Hence, local voltage and current–voltage (I–V) characteristics of the interfaces and spatially resolved impedance spectra of complex microstructures can be obtained. SIM/SSPM technique allows the local properties to be measured with a resolution of ~100 nm.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

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